DYNAMIC RESOURCE SCHEDULING FOR REAL-TIME GROUP BROADCASTING IN 6G CELLULAR VEHICULAR NETWORKS

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Abstract – *Vehicle-to-Vehicle (V2V) messaging is an indispensable component of connected autonomous vehicle systems. The 3rd Generation Partnership Project (3GPP) is designed to support V2V communication without any infrastructure using sensing-based Semi-Persistent Scheduling (SPS) in order to avoid resource collisions for Cooperative Awareness Messages (CAMs) transmission. However, the legacy system suffers from significant collisions in a traffic congestion environment and resource waste in light traffic conditions. To address these problems, in this paper we propose a novel dynamic resource scheduling algorithm for real-time group broadcasting, inspired by the Lyapunov optimization framework, where the optimization objective is to minimize time-average failure probability subject to queue stability. Through extensive simulations, we show that the proposed scheduling algorithm outperforms the standard in both traffic jams and leisurely road environments.*

Keywords – Cooperative awareness message (CAM), dynamic resource allocation, group broadcasting, LTE-V2X, V2V communication

1. INTRODUCTION

Vehicle networks are essential to provide advanced safety for connected and autonomous vehicles [1]. The 3rd Generation Partnership Project (3GPP) defines new Physical (PHY) and Medium Access Control (MAC) layers for Vehicle-to-everything (V2X) communication. The first V2X standards were based on the Long-Term Evolution (LTE) in Release 14 [2, 3], and developed new standards based on New Radio (NR) in Release 16 with minor differences such as flexibility in subcarrier spacing and support various transmission (e.g. unicast, multicast, and broadcast). NR-V2X is not completed, we consider LTE-V2X for this paper. According to 3GPP [4], LTE-V2X defines two new resource allocation modes for V2X sidelink communication: i) mode 3 supports that the base station manages the sidelink communication (equivalence to mode 1 in NR), ii) mode 4 operates without cellular infrastructure support although the UEs could be in eNB coverage (equivalence to mode 2 in NR).

LTE-V2X communications consist primarily of small-scale broadcast packet exchanges with important latency and reliability requirements such as Cooperative Awareness Messages (CAM) or Basic Safety Messages (BSM) to regularly provide basic information such as the location, direction, speed, and acceleration of the transmitting vehicle [5, 6, 7]. To guarantee reliability and robustness of message transmission, LTE-V2X adopts a sensing-based Semi-Persistent Scheduling (SPS) algorithm in mode 4 that vehicles autonomously select their resources without the assistance of the base station [8, 9]. However, LTE-V2X mode 4 suffers from: i) significant collisions in a traffic congestion environment and ii) resource waste in a light traffic environment. To address these problems, this paper tackles the sensing-based SPS algorithm in mode 4, and enhances to SPS for real-time systems. Moreover, a fog-based integrated system is one of the key technologies for faster computing and security enhancements in 6G V2X. Therefore, this paper considers fog-based architecture, and proposes a dynamic resource scheduling algorithm for real-time group broadcasting in 6G cellular vehicular networks. The proposed algorithm adaptively controls a sensing window to each vehicle to improve resource utilization according to density of traffic. The contributions of this paper are threefold:

- We propose a novel dynamic resource scheduling algorithm for real-time group broadcasting, inspired by the Lyapunov optimization framework, where the optimization objective is to minimize the time-average of the failure probability subject to queue stability.
- First, this article represents the first attempt to optimize communications both in heavy traffic conditions and sparse traffic.
- Lastly, based on data-intensive performance evaluation results under various simulation settings, the proposed algorithm is verified to minimize time-average failure probability while maximizing resource utilization.

The remainder of this paper is organized as follows. Section 2 summarizes resource scheduling in 3GPP. Section 3

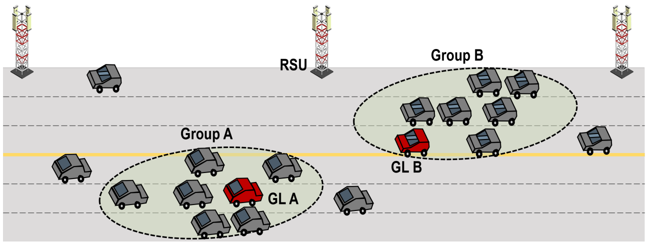


Fig. 1 – Group broadcasting example

presents our system model and proposed dynamic resource scheduling algorithm. Section 4 presents a thorough performance evaluation; and Section 5 concludes this paper.

2. VEHICULAR COMMUNICATIONS BASICS

This section presents a brief overview of group broadcasting procedure (Section 2.1) and semi-persistent scheduling in LTE-V2X (Section 2.2).

2.1 Group broadcasting procedure

NR-V2X supports group communication, where vehicles are organized in groups with a Group Leader (GL) vehicle and multiple vehicles (members) as shown in Fig. 1 [10, 11]. The GL vehicle guides resource configuration and scheduling of the entire group, even when edge member vehicles communicate with each other. The whole group broadcasting procedure can be divided into three phases [12] where the following is determined: i) the configuration of resources to be used for group communications, ii) the selection of resources from the provided configuration, and iii) the allocation of resources for each group member from the selected resources. We briefly describe the phases:

- **Configuration of resources:** The configuration of resources is determined by the Roadside Unit (RSU) via broadcast signalling (SIB) or dedicated signalling (RRC).

- **Selection of resources:** The GL vehicle selects resources for the member vehicles of the entire group. The RSU has configured a resource pool for the group. In order to select resources for the group members, the member vehicles send scheduling requests to the GL. The GL selects resources for the members requesting resources on a sequential first-come-first-serve basis.

- **Allocation of resources:** The GL informs the members of the allocation of resources using RRC signaling in a unicast manner. If the resource pool is configured by the RSU, or if the GL has selected a resource pool for the entire group, the GL instructs the group members to carry out sensing within this pool of resources for individual transmissions among the members (sensing on option), whereas the GL individually signals to the members the resources they must utilize for communication within the group, without any further sensing (sensing off option). The option to switch sensing on or off implicitly indicates to the member as to whether the selected resources are to be shared among members or if the resources are dedicated for the member, respectively.

2.2 Resource selection procedure

LTE-V2X supports channel bandwidths of 10 and 20 MHz in the 5.9 GHz frequency band. The frame structure of LTE-V2X consists of subframes in time domain and subchannels in frequency domain. The subchannel consists of a group of Resource Blocks (RBs), and the number of RBs per a subchannel. Based on fixed resource configuration, each vehicle monitors and selects the resources using the SPS of LTE-V2X, which is operating in mode 4 in order to self-allocate resources. Fig. 2 illustrates the SPS procedure, which is described in continuation and adapted from [8, 9].

- **Channel sensing:** In order to sense the channel, each vehicle continuously measures the Sidelink Received Signal Strength Indication(S-RSSI) on each subchannel every subframe in a predefined sensing window, typically 1,000 subframes.

- **Create list:** Vehicles need to reserve a new subchannel at a subframe in $[n + T_1, n + T_2]$, where $T_1 \leq 4$ and $20 \leq T_2 \leq 100$. Candidate Single-subframe Resources (CSRs) are selected after filtering out two unusable groups of resources.

  Have not been monitored: Due to half-duplex limitations, a node cannot sense during transmission.

  Are estimated as used: Out of all remaining candidate resources, those that are reserved or where a Physical Sidelink Shared Channels (PSSCH) Reference Signal Received Power (RSRP) measurement is higher than the threshold are excluded.

- **Selection:** Based on the create list phase, the first list of available resource list L_A is decided. If L_A is less than 20% of the entire selection window, the RSRP threshold is increased by 3 dB in each iteration in order to get more candidate resources. Otherwise, choose those with the smallest RSSI values, which we call L_B. Then, the vehicle randomly selects a candidate resource of L_B for the first transmission.

- **Reselection:** The number of times that the subchannels for the selected resource is used without the selection process is also randomly selected and is called Reselection Counter (RC). When RC is equal to 0, a new resource must be selected and reserved with probability $1 - P_k$, where P_k is a probability within $[0, 0.8]$. Otherwise, the UE continues to use the current resource.

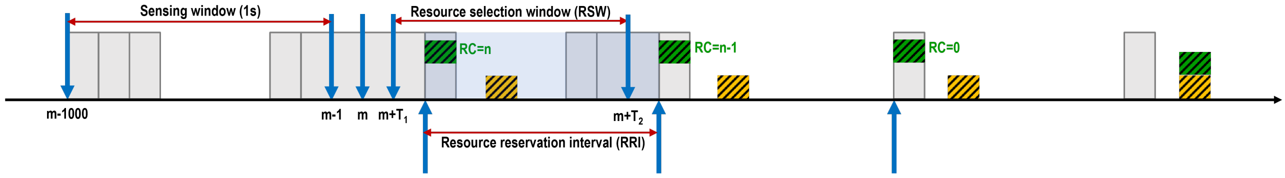


Fig. 2 – Sensing-based SPS scheme timeline

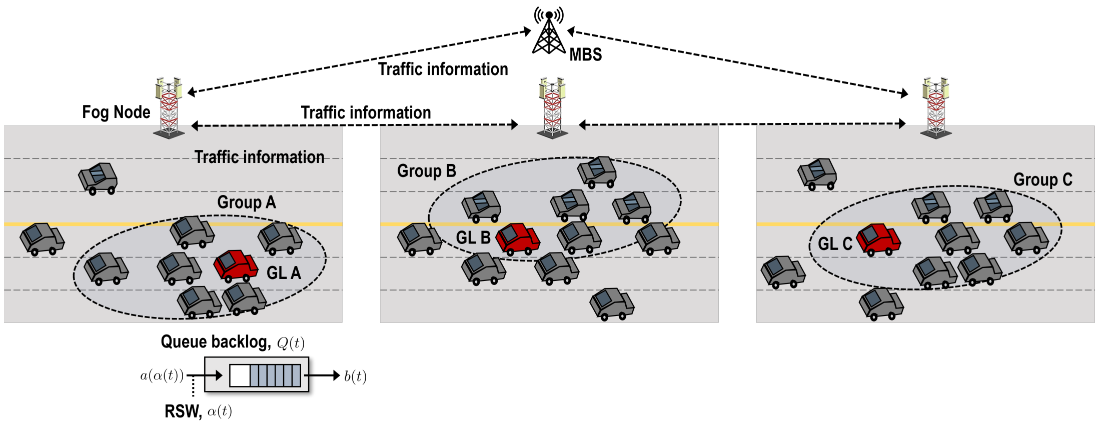


Fig. 3 – System model: Fog-based real-time group broadcasting model

3. DYNAMIC RESOURCE ALLOCATION ALGORITHM

This section presents the problem formulation and algorithm design (Section 3.1), proposes the Lyapunov-based dynamic resource allocation algorithm for real-time group broadcasting (Section 3.2), and describes the pseudo-code and algorithm computational complexity (Section 3.3).

3.1 Algorithm design

A fog node-based system has multiple interconnected layers and could interact with the edge nodes. The fog node helps vehicular communication to achieve low-latency services and group broadcasting services. To this aim, the overall architecture of our proposed algorithm is presented in Fig. 3. The objective is to control the Resource Selection Window (RSW) dynamically based on the vehicle density.
We further describe the entire computation processes considered in our method.

- **Step 1 (Grouping):** The fog node groups the vehicles and determines a GL. The fog node sends a MSG 1 to the GL containing information about member vehicles.
- **Step 2 (RSW decision):** Based on the Lyapunov optimization framework, the GL selects the length of the RSW in each time unit. The GL broadcasts an MSG 2 to member vehicles within the range containing the determined RSW.
- **Step 3 (Resource allocation):** The GL and member vehicles monitor and select the radio resources using the sensing-based SPS scheme with the determined RSW.

3.2 Lyapunov-based dynamic resource allocation algorithm for real-time group broadcasting

In Fig. 3, each GL vehicle has a receiving queue whose update rule is as follows:

$$Q[t+1] = \max\{Q[t] + a(\alpha[t]) - b[t], 0\}, \qquad (1)$$

where $a(\alpha[t])$ and $b[t]$ are the arrival and departure processes, which both are influenced by the length of the RSW, at time t. $\alpha[t]$ is the control action, which corresponds to the length of the RSW in the proposed algorithm. The objective of our optimization problem is to minimize the time-average probability of reception failure subject to queue stability. Each GL vehicle can decrease or increase the RSW length, which affects the total number of resources N as follows:

$$N = \alpha[t] \cdot \left\lfloor \frac{N_{\text{RB}}}{N_{\text{PSCCH}} + N_{\text{PSSCH}}} \right\rfloor. \qquad (2)$$

In the frequency domain, N_{RB} is a number of RBs in a single subframe (50 RBs in 10 MHz, 100 RBs in 20 MHz), N_{PSCCH} and N_{PSSCH} are the number of RBs for scheduling assignment and data, respectively. Therefore, the RSW length affects the failure probability. If the RSW decreases, the number of resources that can be selected also decreases, then the failure probability increases. Nevertheless, broadcasting information is transmitted frequently. Otherwise, the failure probability decreases, and information is transmitted less frequently. The objective is the RSW length control in order to achieve time-average failure probability minimization subject to queue stability, that is:

$$\text{min} : \qquad \lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} P_f(\alpha[\tau]), \tag{3}$$

$$\text{subject to} \qquad \lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} Q[\tau] < \infty. \tag{4}$$

By exploring the trade-off between utility (*i.e.*, failure probability) and latency, the Lyapunov optimization can be used for optimizing the time-average utility function subject to stability of the queue [13, 14, 15]. Then, the Lyapunov function is given as $\mathbb{L}(Q[t]) = \frac{1}{2}(Q[t])^2$. According to [16, 17], the upper bound on the conditional Lyapunov drift is as follows:

$$\begin{aligned}\Delta(Q[t]) &= \mathbb{E}[\mathbb{L}(Q[t+1]) - \mathbb{L}(Q[t])|Q[t]] \\ &\leq C + \mathbb{E}\Big[Q[t](a[t](\alpha[t]) - b[t])\Big|Q[t]\Big],\end{aligned} \tag{5}$$

where C is a constant, and the following holds

$$\frac{1}{2}\mathbb{E}\Big[a^2(\alpha[t]) + b^2[t]\Big|Q[t]\Big] \leq C, \tag{6}$$

under the assumption that the arrival and departure processes are upper bounded. Given the fact that C is a constant and $b[t]$ is not controllable, the upper bound is [18, 19],

$$V\mathbb{E}\Big[P_f(\alpha[t])\Big] + \mathbb{E}\Big[Q[t]\cdot a(\alpha[t])\Big], \tag{7}$$

where V determines the trade-off between the failure probability and delay in the utility function. Here, based on the fundamental theory of Lyapunov optimization [16], the problem of minimizing the time-average failure probability (7) subject to stability, can be formulated as the following closed-form equation, *i.e.*,

$$\alpha^*(t) \leftarrow \arg\min_{\alpha(t)\in\mathcal{A}} \Big[V\cdot P_f(\alpha[t]) + Q(t)a(\alpha[t])\Big], \tag{8}$$

where $\alpha^*[t]$ is the optimal selection window length at time t and $\mathcal{A}$ is a set of possible RSW values. The length of RSW effects the failure probability, P_f, between the transmitting vehicle and interference vehicles. There are two types of interfering vehicles: i) a vehicle that performs a reselection process simultaneously with a transmission vehicle (v_r) and ii) a vehicle that was not recognized in the previous time slot, but has newly become a neighborhood vehicle of a transmission vehicle (v_n) [20, 21]. Then, P_f can be calculated as follows:

$$P_f = 1 - \prod_{v_i\in\{v_r,v_n\}} \Big[1 - p_{col}(v_i)\Big], \tag{9}$$

Algorithm 1 Proposed dynamic resource allocation algorithm for real-time group broadcasting

Initialize:
1: $t \leftarrow 0$;
2: $Q[t] \leftarrow 0$;
3: Decision Action: $\forall\alpha[t] \in \mathcal{A}$
Dynamic resource allocation algorithm:
4: **while** $t \leq T$ **do** // T: operation time
5: Observe $Q[t]$;
6: $\mathcal{T}^* \leftarrow \infty$;
7: **for** $\alpha[t] \in \mathcal{A}$ **do**
8: $\mathcal{T} \leftarrow V\cdot P_f[\alpha[t]] + Q[t]\cdot b[\alpha[t]]$;
9: **if** $\mathcal{T} \leq \mathcal{T}^*$ **then**
10: $\mathcal{T}^* \leftarrow \mathcal{T}$;
11: $\alpha^*[t] \leftarrow \alpha[t]$;
12: **end if**
13: **end for**
14: **end while**

where p_{col} is the probability that a transmitting vehicle and its interfering vehicles $v_i \in \{v_r, v_n\}$ select the identical resource. The probability p_{col} can be expressed as follows:

$$p_{col}(v_i) = \frac{O_c(v_i)}{|L_A|^2}, \tag{10}$$

where $O_c(v_i)$ is the number of overlapped CSRs, which is assumed to be proportional to the ratio of overlapping sensing range between the two vehicles in the self-sensing range. $O_c(v_i)$ is [21]

$$\begin{aligned}&O_c(v_i) \approx \\ &\quad (|L_A| - 0.04N)\Big(\frac{2}{\pi}\text{arccos}\frac{d_i}{2r} - \frac{d_i}{\pi r}\sqrt{1 - \frac{d_i^2}{4r^2}}\Big) \\ &\qquad + 0.04N,\end{aligned} \tag{11}$$

where d_i is the distance between the transmitting vehicle and interfering vehicle, and r is the sensing range, respectively.

3.3 Pseudo-code and computational complexity

The pseudo-code of our proposed method is shown in Algorithm 1. From (line 1) to (line 2), the method initializes the parameters. In (line 5), the queue-backlog $Q[t]$ is observed. From (line 6) to (line 13), the main procedure of our proposed method, *i.e.*, (8), is executed. With the finite RSW decision action space, where all possible RSW decision actions are defined, our proposed method solves the problem by computing closed-form equations iteratively. As a consequence, the run-time computational complexity is only $O(\mathcal{N})$, where $\mathcal{N}$ is the size of the action space, *i.e.*, $\mathcal{N} = |\mathcal{A}|$. Therefore, our proposed method guarantees a low run-time computational complexity.

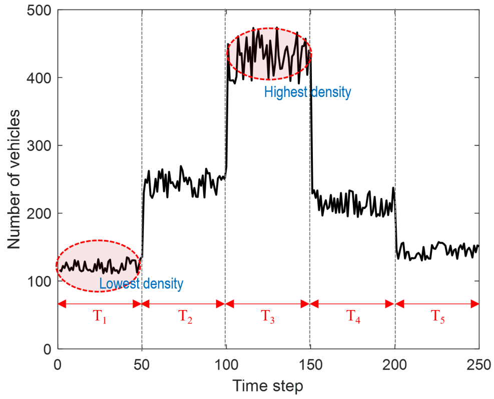


Fig. 4 – Traffic volume environment for simulation: Average number of vehicles varying every 50 time step (The average inter-vehicle density are 10.3, 20.6, 36, 18, and 12 vehicles per 1 km).

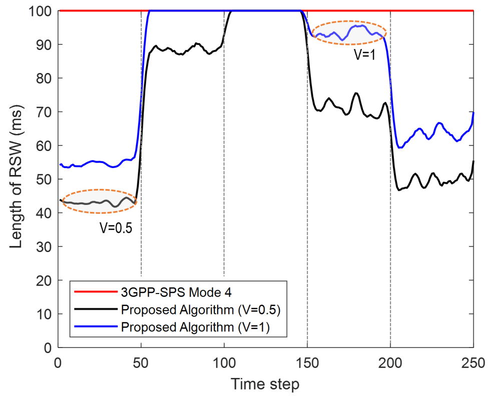


Fig. 5 – The length of RSW for 3GPP SPS mode 4 and proposed algorithm (Case 1: V=0.5 and Case 2: V=1).

4. PERFORMANCE EVALUATION

This section presents the performance evaluation settings (Section 4.1) and results (Section 4.2), respectively.

4.1 Evaluation setup

We evaluate and compare the proposed algorithm with the legacy SPS scheme of cellular-V2X mode 4 (denoted as 3GPP-SPS Mode 4). The simulator implements the full MAC layer of cellular V2X mode 4, including the SPS method. The simulation assumptions are defined according to 3GPP [4], and the scenario implements a 2 km freeway scenario with six lanes. The radio propagation is modeled using the WINNER+ B1 path-loss model and a log-normal distribution is used to model shadowing.

In the simulation environment setting defined in 3GPP, inter-vehicle channels are considered in urban and freeway cases [4]. The freeway consists of six lanes (three lanes in each direction) and has a 2 km highway section. Two values for the vehicle speeds are considered, i.e., 70 and 140 km/h. The average inter-vehicle density are 20.6 and 10.3 vehicles per 1 km when the corresponding vehicle speeds are 70 and 140 km/h, respectively [4, 22]. These values are calculated as 123 and 247 which are the total number of vehicles in the two highway conditions, and we adopt these two values at T_1 and T_2 as shown in Fig. 4. For the rest of time step (from 100 to 250), the average inter-vehicle density are 36, 18, and 12 vehicles per 1 km, respectively, every 50 time step (i.e., T_3, T_4, and T_5). Therefore, the traffic environment assumed in this paper shows traffic congestion for T_3 and maintains a leisurely road environment for T_1.

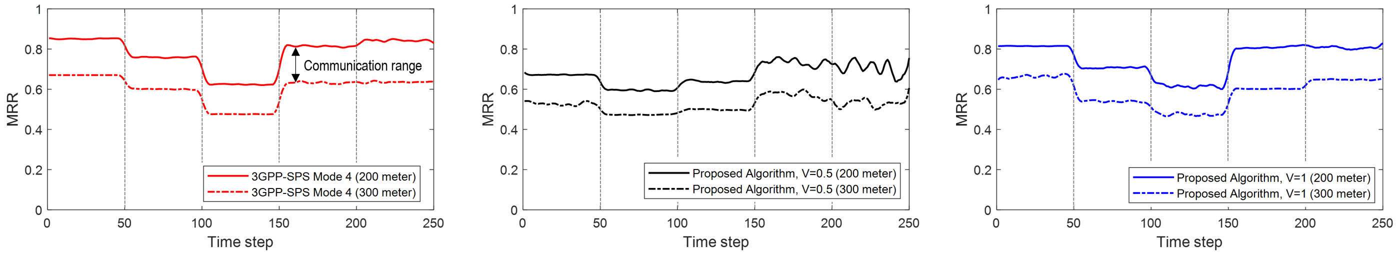
4.2 Evaluation results

Fig. 5 shows the average optimal length of RSW, $\alpha^*(t)$ of the proposed algorithm based on (8). The set of $\alpha(t)$ in $\mathcal{A}$ is $[1, 100]$ subframes, while the legacy SPS algorithm fixes the value to 100 subframes. We set the two types of V determined by the experiment, $V = 0.5$ and $V = 1$. Compared to the SPS mode 4 algorithm, the proposed algorithm conducts the decision-making every time step in order to minimize the time-average probability of reception failure subject to queue stability. A large V emphasizes failure probability, whereas a smaller V enforces queueing delay (resource utilization). If $V \to \infty$, our proposed algorithm selects the maximum length of 100 ms of RSW, which corresponds to the legacy SPS mode 4.

Figures 6 and 7 illustrate the Message Reception Reliability (MRR) and resource utilization for algorithms. Fig. 6 compares MRR calculated by X/Y, where Y is the number of vehicles located in a range at $[0, 200]$ and $[0, 300]$ meter, and X is the number of vehicles with successful reception among Y [23]. The solid curves and the dashed curves are obtained from simulation results with a communication range between the transmitting vehicle and receiving vehicle of 200 and 300 meters. In general, the target range of the standard evaluation methodology is $[300, 320]$ meters [4]. The figure shows that MRR with $V = 1$ is superior to MRR with $V = 0.5$ and is similar to MRR with the SPS mode 4. Fig. 7 shows the resource utilization for different values of V. The resource utilization with $V = 0.5$ is larger than that corresponding to $V = 1$ and the SPS mode 4. Comparing Figures 6 and 7, the two metrics have a trade-off relationship. The MRR at T_3 is the lowest, but the resource utilization at T_3 is the highest due to huge congestion with traffic jams. Otherwise, the MRR at T_1 is the highest, but the resource utilization at T_1 is the lowest due to light traffic congestion.

Fig. 8 compares the empirical Cumulative Distribution Function (CDF) curves of resource utilization achieved by the legacy SPS and our proposed algorithm. In the case of SPS mode 4, there are two colored flat ranges. This results in performance degradation from fixed resource configuration. Since the proposed system dynamically adjusts the selection window, it can provide more vehicle status information as the number of CAM transmissions increases during the entire time.

According to Fig. 9, the proposed algorithm adopts the optimal length of RSW with a predefined V. The length of RSW increases as the number of vehicles increases. The average length of the RSW with $V = 0.5$ and $V = 1$ are 61.17 and 72.37, respectively. In summary, the proposed



(a) 3GPP-SPS Mode 4 **(b)** Proposed algorithm (Case 1: V=0.5) **(c)** Proposed algorithm (Case 2: V=1)

Fig. 6 – The message reception ratio (MRR) for 3GPP-SPS mode 4 and proposed algorithm (Case 1: V=0.5 and Case 2: V=1) within communication range (200 – 300 meter).

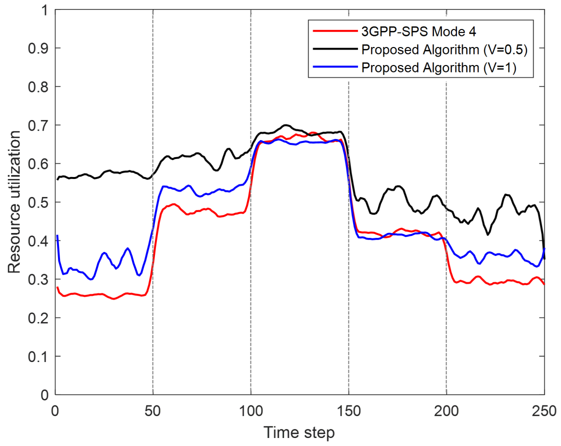


Fig. 7 – Resource utilization for 3GPP-SPS mode 4 and proposed algorithm (Case 1: V=0.5 and Case 2: V=1).

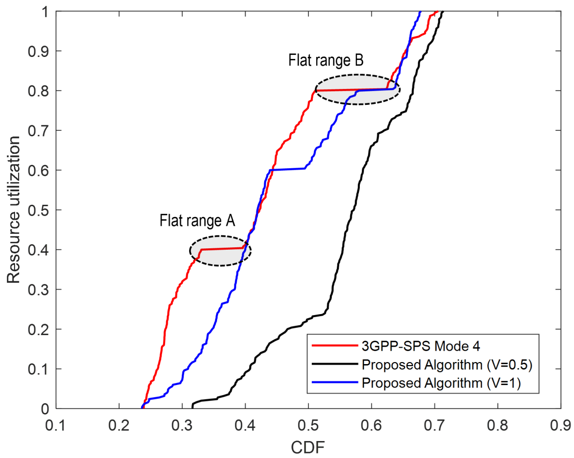


Fig. 8 – Empirical CDF of the resource utilization.

scheme increases: i) MRR, ii) resource utilization, and iii) frequent CAM transmissions due to the reduction of RSW length.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a resource scheduling system to improve the dissemination of cooperative awareness messages. To enable the system to function under conditions of real-time traffic volume, we proposed a

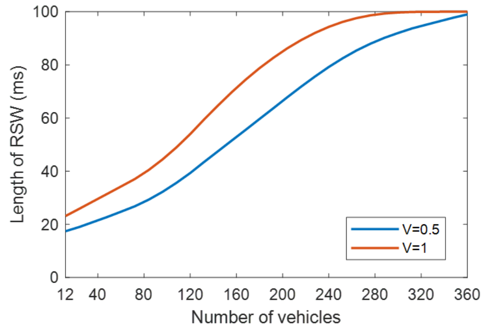


Fig. 9 – The average optimal length of RSW of the proposed algorithm as the number of vehicles increases.

dynamic resource scheduling for real-time group broadcasting. The proposed algorithm computes the length of RSW and for time-average failure probability minimization subject to stability and resource constraints, inspired by the Lyapunov optimization framework. Our simulation results demonstrate that the proposed scheme successfully delivers CAM with low latency and at a high traffic, particularly under heavy road traffic conditions.
As future research directions, we will consider more advanced and realsitic resource allocation in vehicular networks, e.g., wireless blind spots in C-V2X sidelinks and resource allocation modes in C-V2X.

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